How the investigations of the students' reasoning on waves and the history of physics can help us to develop research-based innovative units for secondary students on the velocity of light?

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Abtract : This paper shows how the similarities between students’ conceptions and ancient theories can be used to elaborate innovative pedagogical units. It focuses on a unit dealing with four points revealed or supposed to be difficult for students. They concern the fact that the white light is composed of several “coloured lights”, that the velocity of light is not infinite, is the same for all coloured lights in vacuum, is not changed when light has travelled through a transparent medium. In order to work also on epistemological notions, in particular on the concept of proof and on the limits of models, this unit has been based on texts presenting conflicting theories. It proposes different types of activities and an experimental staging of the texts, when it was possible. Questionnaires are currently distributed in order to collect teachers’ viewpoints on this unit. Test and evaluation of this unit are planned.

Introduction

The new physics’ program of the French secondary schools (1999, 2000, 2001) specify how it is important to show students that science has a history but give little examples. Besides, several science education researchers (Toussaint § Gréa 1996) notice the interest of the history of science in teaching but there are still few examples of pedagogical units based on it, at least in France. Moreover, still few studies (Audigier § Fillon, 1991, Laugier § Dumon 2001, de Hosson 2004) explore the questions raised by the introduction of history of science in teaching whereas they are numerous:

- What aims do we assign to the use of the history of science?
- How do we include history of science in “normal” courses?
- Which is the effect of history of science on the students’ learning, on their image of the nature of the science, on their interest towards scientific studies?

It is why we have started a research program which aims at analysing what is happening now in classes and at designing and testing innovative pedagogical units.

We are in the first stage of this research program. On the one hand, we have already elaborated an innovative pedagogical unit on light, which was published in a pedagogical review in November 2003 (Maurines § Mayrargue). We have chosen this topic because we have both explored it, from the historical side (Mayrargue 2001) or from the “cognitive” side (Maurines 1992, 2001). On the other hand, we have presented this unit in a session training in-service teachers in April 2005. Questionnaires are currently distributed in order to collect teachers’ viewpoints on this unit.

First, we will present you how science education researchers explore students’ difficulties and what they think about the history of science. Second, we will specify what the program says on the use of history of science and on light. Third, we will show you how the investigations on the students’ conceptions on light, more generally on waves, and the history of physics have led us to specify pedagogical contents and methods. Finally, we will give you some information on the teachers' viewpoints.

Science education background

During the last forty years, a considerable amount of attention has been focussed on children and students' ideas in various fields of knowledge, especially in science. Indeed, there is now a general consensus that learners actively build their knowledge from "where they are" and with "what they have". In this constructivist view of learning, it is therefore of crucial importance to know this "spontaneous" or "prior" knowledge in designing teaching content and procedures. However it is not, most of the time, explicitly enunciated by children and students, which are to a large extent unaware of it. It is why numerous studies have been undertaken in order to explore students' ideas on science.

One type of science education studies is content-dependent, in the sense that they explore the students' ideas in a specific domain of science, for example, mechanics, and optics and so on (for a review in physics, see Viennot 2001). A problem, which concerns most of the researchers in this domain, is to avoid giving merely a catalogue of such "intuitive" ideas, and to look for an organisation in these conceptions. Indeed, a synthetic description of the students' thinking is easier to take into account than a list of typical questions and responses, and is likely to yield some cues for more successful teaching –learning strategies. One way of giving meaning and coherence to students' answers is first to focus on the concepts and principles which students use, then to establish a typology of questions-and responses, finally to look for similarities across a variety of physical situations presenting a common feature. Thus, some main trends of reasoning can be shown to recur in a particular domain of physics and to frequently contradict the science taught at school. Now, we have enough studies in different fields of physics to tell more about the spontaneous knowledge: the same few trends of reasoning are observed across different domain contents, for example mechanics, and electricity, and so on. The self-consistency of this spontaneous knowledge probably accounts for the fact that some of its components are extremely resistant to teaching and can even be found in experts.

There is another type of science education studies, which is not content-dependent. They deal with the students' image of the nature of science (Larochelle § Desautels 1991, Driver et al. 1996). They explore questions such as what is, for students, the nature of the scientific knowledge (that is to say the nature of the theories, of the models, of the laws), what is the nature of "the" scientific method, and so on. These studies reveal in particular that, for many students, the observation is not influenced by theories that scientists hold, that scientists do not invent laws but interpret the laws found in nature, that models are nearly similar to the real entities that serve as the subjects of modelling. This empiricist view of science is sometimes mixed with a constructivist view of science: for many students, scientific laws are only scientists' best efforts to explain nature and a step towards truth.

Following Bachelard (1934), Halbwachs (1974), Piaget et Garcia (1983), science education researchers sometimes enjoin to refer to the history of science in order to investigate students' conceptions (Joshua § Dupin 1993, Martinand 1993). Indeed, as some similarities with ancient physical theories have been stressed on, the history of science is seen as possibly inspiring some hypotheses on students' ways of reasoning. But this use of history of science in research has to be questioned. Following Saltiel and Viennot (1985), we think that it is unreasonable to look at a strict parallel between students' ideas and ancient theories. Indeed, the cultural contexts are different and all the features observed in spontaneous reasoning today have not necessarily occurred simultaneously at any one definite stage in the historical development of the theory. On the other hand, we might hope pieces of information about our students from the history of science, providing to look for the long-term resistances it manifests.

Hypotheses on the students' difficulties are not the only benefits, which we can expect from an analysis of the historical development of the science. This analysis can also bring to the fore experiments and questions, which seem to have been fundamental problems in the past and crucial steps in the construction of the theory, and which are forgotten in teaching nowadays. The pedagogical propositions, to which they lead us, are based on the hypothesis that arguments of reasoning employed by the past can be reapplied today, helping students who face similar problems of comprehension (for example, see Galili and Hazan, 1999). Still there, it seems unreasonable to suppose that students' thought will transform and evolve exactly the same way as in the history of science. We can only hope that presenting students these forgotten situations, we give them the opportunity to confront the conflicts between the accepted theory and their own reasoning, and a greater chance to reach a meaningful learning of the subject matter.

The pedagogical suggestions derived from an historical analysis are of two types: some are inspired by historical situations but do not refer to it, others enjoin to introduce pieces of the history of science in courses. This explicit reference to history in teaching is also often recommended by researchers in order to show students a more realistic picture of the ways science is built up and evolves.

The physics' programs of the secondary schools in France

In most recent secondary school programs, the history of science is often mentioned as a learning device for both junior and high schools. This course of action is relatively recent, and you might think that this new perspective has already made headway in the framework for the fight against boredom felt by science students not only in France, but also in all western countries. Furthermore, you might think it was necessary to go beyond the view that teaching science is not only to present students methods and results but also the socio-historico-cultural aspects. Besides, you might also think that helping at a better understanding of the epistemological and historical context along with its controversies can actually contribute to the acquisition of knowledge.

The people who developed the educational programs organised the benefits of the history of science into two categories: those for the teachers and those for the students.

More than the learning device that it is, the history of science seems to be included in educational programs for middle high school[1] in order to pique students' interest. Assuming that students will already be interested in epistemology and history of science, and assuming that students have access to the materials, they propose to discover the life of a famous inventor, the evolution of a particular object, and the evolution of a technique. They also propose the use of texts in which their characteristics are to avoid any unnecessarily complicated term, to do not hesitate to include the anecdotic aspects ("little history"), and to establish the link between the inventor or the discovery and the geographical, historical, cultural and social context.

These aspects are tackled and developed when they are addressed to older students[2]. It was established that it is still possible to teach the sciences, in particular the physical sciences, by making no reference to history, and that we are henceforth confronted with problems, notably the lack of students' motivation. Thus, the programs of high school propose to take up a hypothesis, which is taken for granted: oral presentations of past controversies and of the evolution of ideas must contribute to the nourishment of students' curiosity. Another hypothesis is that the use of the history of sciences, and in particular its oral presentation, allows for the recontextualisation of concepts which may contribute to a constructivist dynamic of knowledge. This should call students to question themselves, or at least, making them understand the "mechanism of questioning"[2].

In the materials for the 12th grade science program, the role of epistemology and history of science is explained. It is part of a cross-curricular approach, which should have the effects of actually being able to see the "content taught" transformed by this program selection. [3] This is true in various fields of study such as mechanics and the travel of waves. A large role is attributed to the use of documentary texts which allow students to understand "how science develops knowledge and […] questions nature" [4], to know the history of the subject, and to go beyond the simple transfer of data. In a word, it is a matter of knowing "how to proceed in science". Finally, the importance of context is highlighted in the programs.

Through this analysis, you can see a considerable amount of progression in the programs inasmuch as epistemology and history of sciences is not at all an unimportant field. With such a process, teachers have 3 main concerns, which are the evolutionary character of knowledge, the close link between sciences and technology, and the relationship between science and technology and their socio-cultural context.

This brings me to talk about the particular question of optics in the program from an historical point of view. The study of optics is very ingrained in teaching at the secondary level in various ways. For grade 7 and 8, it is a matter of answering the following questions, which echo our ancestors' question : " how can one see? " For grade 10 and 12, one will seek to answer questions concerning nature of the light: Is the light homogeneous, heterogeneous? In echo, one find again "what is Light? "of Descartes and its successors

Topics of the innovative pedagogical unit

The pedagogical review asked us to elaborate a unit for the last period of high school. As in grade 12, which is the class of baccalauréat, teachers are in a hurry, we chose to realise a unit for the grade 10 (aged 15-16). The unit relates on two topics of the program of this level: the velocity of light and the coloured lights.

As it is important in a constructivist view of learning to work with students on trends of reasoning particularly resistant to teaching, <u>we choose to focus the unit on four points revealed by science education researchers as difficult for students or that can be difficult with two hypotheses.</u>

The first hypothesis is that the mechanistic reasoning put forward for the propagation of a signal on a rope (Maurines 1992) and a sound signal (Maurines 1993, in Viennot 2001) can also be encountered for light. This means that we suppose that students consider the signal, whatever it is, as a material object, which moves according to the laws of dynamics. More precisely, this means that students do not consider the propagation velocity as a constant, characteristic of the propagation medium. For them, the signal velocity depends on the initial conditions like a ball when it is thrown upwards by a hand, and can decrease with time like a solid submitted to friction.

Let give an example of such reasoning.

When students are asked whether a given point of a rope can move earlier, a majority of them (W_0, 60%, N=42; W_1, 75%, N=16) answer that there is a way of moving the hand, which holds one end of the rope, so that the signal travels more quickly[1]. Most of the corresponding justifications mention the force used by the hand to create the signal and say "the stronger the force, the greater the propagation velocity": *"the bump will move faster if the shake is sharp", "the speed depends on the force given by the hand", "If the intensity of the force which is propagated is stronger, so the signal will spread more quickly too".*

Here is another example.

When students are asked whether the velocity of a bump which disappears before reaching the other end of the rope is constant, most of the students (W_0, 68%, N=56; W_1, 55%,, N=42) mention a decrease of the velocity. Here also the justifications that mention force are numerous. They again point out that the force used by the hand at the start seems stored in the bump. Moreover, this force seems materialised in the signal amplitude. When this amplitude decreases, this "force" and consequently the propagation velocity decrease simultaneously: *"the height decreases as the action of the hand is getting weaker", "if the bump disappears, it is because the force which caused it disappears as well. During that time, the speed decreases".*

The same kinds of questions have been elaborated for the propagation of sound and the same kinds of answers have been obtained. What students call "force" is in fact something that has been given to the signal by the source at the start, something moving on and staying in the signal. It is a mixture of force, energy, speed...The cause and the effect are confused so that the reasoning used by students is based on a single notion. As this trend of reasoning is close to the one put forward by Viennot (1977) and Saltiel (1978) in the mechanics of the solid, the notion, on which this reasoning is based, has been called a supply. The following table stresses on the similarities between the answers given by students in the case of the propagation of a bump on a rope, of a sound signal and of a ball thrown upwards by a hand.

Visible signals (Maurines, 1992)	Sound signals (Maurines, 1993)	Object (Viennot, 1977)

If the children <u>can give the same force</u>, the bumps will have the same speed	*she hears Peter first because the sound is higher and <u>is thrown more quickly</u>*	*a certain movement, force, speed <u>has been given</u>*
if the bump disappears, it is because <u>the force which caused it</u> disappears as well. During that time, the speed decreases	*the sound is reducing more and more and so goes slower*	*the <u>force given by the man</u> is diminishing more and more*

In the case of light, we do not know any study focussed on the particular subject of the light velocity. Nevertheless, some signs can be found in a research made by Lefèvre in France in 1988, which led us to suppose that students use the same reasoning. Thus, one third of the students in their first year of scientific studies at university (N=176) agree with the following affirmation: "*the ocean deeps are dark because sunlight goes through the surface, slows down and stops at a certain depth*". Moreover, the same reasoning in term of obstacles are encountered in the case of light and sound. Thus at a question asking students to class the velocities of sound in four different medium (vacuum, air, liquid, solid), students give such answers : *"the sound velocity depends on the propagation medium. It is braked down by the collisions with the more or less numerous molecules of the medium: water , air, vacuum"*(Maurines 1993). This kind of answer is close to the one obtained by Lefèvre: *"it is slower when there are more obstacles. In vacuum it is going quicker. In the air, a little slower. In liquids, still more slower."* We could also probably explain some answers obtained by Perales et al. (1989) in assuming a link between the intensity and the velocity of light: for 11% of the 44 trainee teachers he questioned in Spain, a lens increases the velocity of light that passes through it.

<u>The mechanistic reasoning presented here led us to choose to work on factors, on which the light velocity does not depend.</u> We focused on two points: the fact that the velocity of light is the same for all coloured lights in vacuum and the fact that it is not changed when light has travelled through a transparent medium. <u>It has to be noticed that the program does not ask teachers to work these points. It only says to give students the numerical value of the velocity of light.</u>

The unit examines two other points, which are in the program and which we suppose to be difficult for students: the fact that light has a finite velocity and the fact that white light may be considered as composed of several "coloured lights". Indeed, we have not found many informations on the difficulties encountered by students on these particular subjects. Most of the studies on the students' conceptions on colour focus on the colour of opaque coloured objects and not on the production of colours from white light (Chauvet 1994). The investigations on the students' conceptions on vision and shadows do not focus on the question on the value of the light velocity. However, some results (Guesne 1985, Kaminsky 1989) let us suppose that light seems no conceived by children (under 12) as "travelling" and having a finite speed. Indeed, light is not considered to exist independently in space: light is associated only with a source or with a bright spot and its effect is instantaneous. Some studies (Hadaddah 1984, Prat 1989) let us suppose that the white light may be considered as homogeneous and that the subtractive synthesis of colours raises difficulties (Saxena, 1991)

By choosing these two points, we assume that students can have the same difficulties nowadays as scientists had to overcome formerly. This second hypothesis on the students' difficulties is inspired by the similarities between students' conceptions and ancient theories noticed by several science education researcher in different fields (Viennot 1977, Saltiel 1978, Mc Closkey 1983, Clément 1983, Benseghir, 1989, Sanmarti § Izquierdo, 1995, Galili § Hazan, 1999). It and is reinforced by our own analysis on the particular subject of waves (Maurines 2001, Maurines § Mayrargue 2001).

Objectives of the pedagogical unit

The first objective targeted in this series was to show students that scientists' ideas were in constant evolution throughout history. We think that the concept of the speed of light is a good example : it is in this way that this evolution is important, between Galileo, who formulated notions of light's finite aspect, Römer, who demonstrated the former's theory and Fresnel who elaborated the very meaning of this question by rejecting Newton's presiding theory, this former ended up with a paradigm shift in order to account for all light phenomena.

In the explanation of this series on light, we have been more discriminate than the people who came up with educational programs dealing with optics. More than a "true" / "false" dynamic, we have tried to demonstrate what the stakes are through various work proposals : the very notion of proof. It is thus that proof can be of varying natures: philosophical, experimental and theoretical. [In the case of Galileo, we could ask ourselves the question of the role of rhetoric as a technique of persuasion.] In order to correct "students' false perceptions" [5], we have attempted to focus not only on old-fashioned concepts, but also on the importance of discussion by using diverse strategies such as questioning and argumentation.

A second objective consists of examining the possibility of discussion on the use of analogy, frequent in physics, to explain the concept of light refraction, in this case a mechanist analogy, and to demonstrate its limits. These contradictions had been taken into account and partially resolved by René Descartes in *Dioptrique*[6]. We have concentrated on a thesis by Alexis Clairaut which, long after René Descartes, highlighted that in practice such an analogy would lead to significant contradictions.

A third concern that we had, was to show that a model, in this case Newton's corpuscular model, has its limits, notably when the conclusions which result from it, contradict observation and experiment. Highlighting a model's limitations can provoke a phase of crisis which, by way of consequence, can lead to the emergence of new models. The example that we propose in this series concerns substitution in the Newtonian theory of light, using the wavelength theory put forth by Augustin Fresnel in his analytical observation of a solar eclipse.

Choice of texts

We have to choose texts dealing with the velocity of light and the origin of coloured lights.

1. Speed of Light

Texts discussing light and its possible travel are numerous. This sheer abundance demonstrates that this question was central and that multiple answers were possible. One of the common concerns of these texts is the question of proof.

If you want to thrash out problems dealing with the speed of light, as educational programs encourage, you must first ask yourself the question if light travels. Beyond this question, if you admit that light travels, then you can pick up a text by Galileo, written in the form of a dialogue, which poses the problem of the speed of light. It doesn't resolve problems dealing with speed, but the formula, as Einstein and Infeld[7] pointed out, is oftentimes "more important [...] than coming up with a solution based on mathematical or experimental prowess". This text, which calls for both rhetoric and thought experimentation, focuses on an "imaginary" experiment as well as on a particularly developed line of argument whose significance could be interesting to study[8]. Written by Galileo to discuss the finite aspect of the speed of light, the dialogue is easily utilizable or even played out in class, allowing for a qualitative approach to the question. It seemed to us that the dialogue could be motivating and convincing to students thanks to the text's dialogue format.

From another point of view, the more philosophical but also more sense-oriented Descartes was led to assert that the speed of light was infinite. His demonstration, which we cannot reproduce here given the limitations of our facilities, is interesting since it focuses on an analogy.

Römer adopted a different strategy. He gave experimental proof of the finite aspect of the speed of light by focusing on fields of science other than optics, like astronomy. We have made reference to an article written by Römer that appeared in *Le Journal des Scavans*. Even if it contains some delicate reasoning, it is a classic starting point dealing the notion of proof since it focuses in a few simple calculations, derived from astronomical observations, which help demonstrate the finite characteristic of light.

With Augustin Fresnel, it is a matter of showing that a certain way of thinking can lead to discussion about the validity of a model. Arguments of a theoretical nature are often useful for invalidating one model and at the same time validating another. Here we are referring to a text written by Fresnel at the beginning of the 19th century in which he discusses Newton's theory of light with the intention of proving it false.

Thus, we have purposely chosen diverse argumentative methods by way of texts originating from very different historical periods of modern science.

2. The Origin of Color

Is white light homogeneous or heterogeneous? That is the question that you are led to ask yourself when you wonder about the origin of color. Two models, developed respectively by De Dominis and Newton , seemed well adapted to 10th grade students.

De Dominis took up the ancient Aristotelian theory, the theory of modification; in this theory which focused on sense-oriented experimentation, white light was supposed to be pure and homogeneous. Color was born from an alteration of this light by dimming or darkening it. Thus, joining De Doninis's perspective that there exists three colors, red would be produced by making white more opaque. The thicker part of the prism produces green and then purple. The other colors were derived from the latter.

On the contrary, Newton postulated that white light was composed of several colors. These colors were revealed by separation thanks to a prism. One of the novelties of his labors was that Newton did not discover the theory of light through this experiment. This experiment was set up by Newton only to check theories he had about the nature of light.

Activities proposed to students

Once the aims of the unit and the texts chosen, we had to decide how to present them to students.

Different types of activities have been proposed.

Some are standard and can be encountered in the program or the textbooks:

- read a text and answer questions (Galilee);
- solve an exercise inspired by a text judged too difficult for students in order to follow the reasoning used by scientists formerly (Römer).

Others are more original and propose an experimental staging of the texts. Our first aim was not to reproduce the experiment presented in the text but to insert the experiments they relate to into problem-solving situations. In this kind of situations, students have to resolve a problem resulting of a conflict caused by their own conceptions. The origin of the conflict may be a contradiction between an experiment and a conception or a contradiction between different conceptions. Teachers have to guide students without giving them the solution and have to recognise the right solution they propose as the solution accepted by the scientists today. As we do not have enough information on how students reason on the refraction and dispersion of light, we could not propose such activities. Also, we decided to insert historical texts into problem-solving situations in order to guide students to construct the new knowledge. So instead of proposing an implicit use of the history of science, we propose an explicit use.

In problem-solving situations, texts can be used at three different moments for three different purposes: at the beginning in order to create a conflict, at the end in order to validate the solution proposed by students, in the middle in order to help students to resolve the problem. In the unit, two methods were proposed:

- in the part dealing with the controversy on the heterogeneous light based on the texts on De Dominis and Newton, students are asked to read conflicting texts, to deduce predictions from the models they relate to before an experiment is done, to propose another experiment in order to validate one of the model.
- in the parts dealing with the factors affecting the velocity of light based on the texts of Clairault and Fresnel, students are asked to predict what happens in a situation, problematic for scientists formerly and forgotten by teaching today, and note how scientists explained it.

Teachers' viewpoints

We have elaborated and distributed questionnaires in order to collect teachers' viewpoints on the use of the history of science in classes before and after the session we organised in April 2005 for in service-teacher. We have still few answers and we cannot give many indications.

However, some points can be noticed on the questionnaire given before the session and filled up by nine teachers.

- Three teachers had lessons on the history of science during their studies: two of them rarely speak about history of science in classes because what they know cannot be applied in classes, one of them often presents anecdotes.
- Six teachers who used the history of science in their classes said how it was difficult for them to do. Two reasons were given: students are not interested, students do not understand the language of the text.

Conclusion

In brief, the assumption that error plays an essential role in the construction of knowledge led us to choose points, which are not explicitly in the program and which are shown or supposed to be difficult for students by science education researchers. The idea that teaching is not only to transmit concepts and methods but also an image of the science led us to choose to work on the students' epistemological conceptions and on points suggested by the most recent program of high school. These are the fact that models evolve, have to be tested experimentally, have limits. The research on innovative pedagogical units and problem-solving situations led us to use historical texts in different ways. Some have inspired exercises or experiments and are not introduced to students. Others are introduced to students and proposed different types of activities: a classical one, which consists in reading the text and answering questions, a more original one, which consists in using texts to made prediction in front of an experiment or in validating results obtained by students.

Let conclude this presentation by telling that in this new dynamic of using history of science in teaching comes the necessity to train physics teachers. This has to be done not only in the domain of epistemology and history of sciences but also in the domain of pedagogical methods. Indeed, the teachers' viewpoints reveal that it is not enough to be informed in history of science. One goal of the training program should be to transform the very positivist and empirical standpoint of a branch of science considered rigorous, objective, incontestable and intransigent. Another goal should be to lead teacher to a positive view of error, the role error plays becomes essential because from it, we are provided with a "motor of knowledge" [9], and examples taken from HSc are plentiful. As Jean-Marc Lévy-Leblond remarks: *"Real scientific work consists in large part of the examination of hypotheses which turned out to be false…teaching of the sciences can contribute to the development of critical thinking skills, as it is supposed to do, only if it gives credence to the critique of science itself and sets relevant goals for its advancement*." [10] . Another should be to show teachers how to elaborate problem-solving situations, in particular those based on the history of sciences.

Notes

[1] Educational materials for the 9th grade program http://www.cndp.fr/archivage/valid/54533/54533-7949-8801.pdf', p. 18.
[2] Taken from the physics and chemistry program for grade 10 http://www.cndp.fr/archivage/valid/17423/17423-5053-4870.pdf', p.9
[3] Documentary materials for 12th grade science, p. 5 http://www.cndp.fr/archivage/valid/38815/-38815-5719-5536.pdf
[4] ibid., p. 59
[5] Educational materials for grade 8, p. 18. http://www.cndp.fr/archivage/valid/54533/54533-7949-8801.pdf
[6] Descartes, Dioptrique, p. 171
[7] Einstein and Infeld, p. 89.
[8] Spranzi-Zuber
[9] To be taught at the junior high level, physics and chemistry, Nov. 2003, p. 28 http://www.cndp.fr/archivage/valid/54533/54533-7950-8802.pdf'
[10] Lévy-Leblond J-M., « Eloge des théories fausses », in L'esprit de sel, Seuil, 1996, coll. « Point Science ».

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